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Effects of stop signal modality, stop signal intensity and tracking method on inhibitory performance as determined by use of the stop signal paradigm

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In Experiment 1, the effects of stop signal modality on the speed and efficiency of the inhibition process were examined. Stop signal reaction time (SSRT) and inhibition function slope in an auditory stop signal condition were compared to SSRT and inhibition function slope in a visual stop signal condition. It was found that auditory stop signals compared to visual stop signals enhanced both the speed and efficiency of stopping. The modality effects were attributed to differences in the neurophysiological processes underlying perception. However, Experiment 2 demonstrated that the modality difference was larger for 80 dB(A) auditory stop signals than 60 dB(A) auditory stop signals. This effect was reconciled with the suggestion that loud tones are more capable of eliciting immediate arousing effects on motor processes than weak tones and visual stimuli. The second purpose of the present investigation was to explore the utility (and potential advantages) of an alternative way of setting stop signal delay relative to mean reaction time (MRT). The method that was suggested compensates for inter-individual differences in primary task reaction speed by setting stop signal delays as proportions of the subjects' MRT.

Key words: Stop task, motor inhibition, stop signal modality, stop signal intensity, tracking method.

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INTRODUCTION

The motor inhibition process has typically been studied using the stop signal paradigm (Logan & Cowan, 1984), in which subjects perform a primary choice reaction time task and are occasionally presented with a stop signal that instructs them to suppress the response. Logan and Cowan's model accounts for response inhibition in terms of a "horse race" between the go process (triggered by the primary task stimulus) and the stop process (triggered by the sudden presentation of the stop stimulus). The subject succeeds in suppressing his/her response if the stop process finishes before the go process. Since the race model provides a powerful method for comparing inhibitory competence in different conditions and subject groups, the stop signal paradigm has been used in a variety of studies. Especially within the fields of developmental and clinical psychology, stop signal reaction time (SSRT) and inhibition function – the two main dependent variables in the stop signal paradigm – have proved to be valid diagnostic tools for establishing inhibitory deficits. Research in the former domain tries to describe and explain differences in cognitive abilities between young and old subjects in terms of age-related changes in inhibitory capacity (e.g., Bedard, Nichols, Barbosa, Schachar, Logan & Tannock, 2002; Kramer, Humphrey, Larish, Logan & Strayer, 1994; Ridderinkhof, Band & Logan, 1999; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). The latter domain of investigation aims at uncovering the relation between a variety of psychological (childhood) disorders and deficiencies in inhibitory control. For example, the stop signal paradigm has been used to examine the role of inhibitory deficits in attention deficit hyperactivity disorder (ADHD) (e.g., Barkley, 1997; Overtoom, Kenemans, Verbaten, *et al.*, 2002; Pennington & Ozonoff, 1996; Schachar & Logan, 1990) and dyslexia (e.g., Purvis & Tannock, 2000; Van der Schoot, Licht, Horsley & Sergeant, 2000, 2002).

EXPERIMENT 1

In Experiment 1, we focus on two factors – stop signal modality and tracking method – that are inextricable ingredients of the stop task procedure but which have typically been overlooked as possible co-determinants of stop task performance.

Stop signal modality

The early research on stopping has shown that the stop process can be exerted on a wide variety of tasks, whereas the speed of stopping remains relatively constant. The SSRTs of young adults were found to be 200–300 ms when subjects were required to inhibit continuous actions, such as speaking (Ladefoged, Silverstein & Papcun, 1973) and typing (Logan, 1982), or discrete actions, such as responses to different choice reaction-time tasks (see Logan & Cowan, 1984, for a review).

It should be noted, however, that these data come from simple stopping experiments in which there is only one stop signal that requires the non-selective interruption of any and all responses, and in which the performance of stop reactions may be described as the execution of a “prepared reflex” (Hommel, 2000; Woodworth, 1938). A substantial increase in SSRT was found in a selective stopping task, in which subjects had to inhibit one response but not another (Logan, Kantowitz & Riegler, 1986), and in a stop/no-stop task, in which subjects had to inhibit responses when one stop signal was presented but not another (Riegler, 1986). These results suggest that the selective stopping task and the stop/no-stop task require a more complicated stopping mechanism than the single, global mechanism that is supposedly employed in the different simple stopping tasks (see Logan, 1994).

More recent studies showed in a different manner that SSRT is not as invariant as previously assumed (e.g., Kramer *et al.*, 1994; Ridderinkhof *et al.*, 1999; Van den Wildenberg, Van der Molen & Logan, 2002; Van der Schoot, Licht, Horsley & Sergeant, 2003). Van der Schoot *et al.* showed that inhibitory performance is better for stop signals presented in the right visual field than in the left visual field. Other studies examined stop signal inhibition in conditions that required some other form of inhibition. For example, Van den Wildenberg *et al.* showed that reduced response readiness slows down the stopping mechanism, and Ridderinkhof *et al.* found that stop processes were completed more slowly when the imperative signal (a target arrow) was flanked by distractor stimuli that were associated with the incorrect primary response (non-corresponding flanker arrows) and that response suppression in the primary task was less efficient when stop processes were active simultaneously. According to Ridderinkhof *et al.*, these results indicate that the operation of response inhibition in the primary task processes and response inhibition in the stop process affected one another negatively.

In the above examples, the speed of stopping varied as a function of manipulations that acted upon inhibitory processes. In Experiment 1, we raise the question whether differences in stop signal inhibition may also be due to differences in perceptual processes that precede the inhibitory processes. In particular, we examine whether the sensory modality of the event that triggers an inhibitory response may have an effect on the speed and/or efficiency of the stop process. Therefore, SSRT and inhibition function in an auditory stop signal condition were compared with SSRT and inhibition function in a visual stop signal condition. It is hypothesized that stopping performance is better in the auditory condition. This hypothesis is based on the notion that the neural pathway for sound perception is shorter – i.e. has less synaptic transmissions – than the neural pathway for visual perception, and that the (mechanical) reception processes at the ear take less time than (chemical) photoreception at the retina (e.g., Elliot, 1968; Goldstone, 1968; Woodworth & Schlosberg, 1954).

Tracking method

In order to acquire inhibition functions that account for differences between and within subjects in primary task RT, (changes in) mean RT (MRT) must be tracked over time. In the case of block-to-block tracking, MRT is calculated after each block of trials whereupon stop signal delays can be adapted to it in the following block. Stop signal delay is the time interval between the onsets of the primary task stimulus and the stop signal, and setting the stop signal delays relative to MRT comes down to defining specific time intervals between the onset of the stop signal and the computed primary task MRT, i.e. MRT minus delay. While choosing the time intervals, one has to take into consideration that the shortest stop signal delay should approximate zero and the longest stop signal delay should come close to the mean. Subsequently, the intermediate delays can be spaced evenly in between these extremes. Compensating for differences between subjects in primary task MRT by means of this method causes the responses to the stop signal to cut off the primary task RT distributions at comparable points; that is, if measured “backward” from the MRT. If we measure “forward” from the onset of the primary task stimulus, however, the difference in MRT is still manifest in the additional time that passes by – for each defined stop signal delay – before a stop signal is presented to the subject with the slower MRT. As a consequence, a stop signal presented at a particular delay may very well hit different processing stages in subjects substantially differing in MRT. This can be clearly illustrated by comparing hypothetical subject 1 and subject 2 in Fig. 1; only in subject 1, the stop signal presented at the “MRT – x

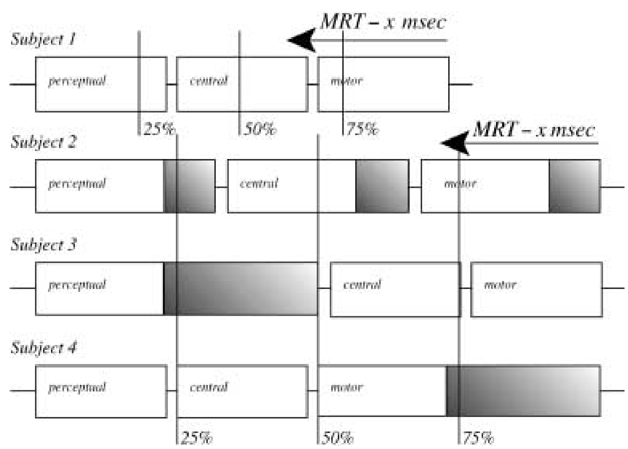

Fig. 1. Illustration of how the processing stage that is hit by a particular stop signal depends on tracking method. Under the assumption that processing stages are equally slowed down in a slow subject (2) compared to a fast subject (1), setting stop signal delay as “% of mean primary task reaction time (MRT)” enables the experimenter to present stop signals at comparable points along the processing-chain (25%, 50% and 75%). Setting delay as “MRT – delay” (MRT – x ms) may cause the stop signal to hit different stages (in particular: premotor stage in subject 1 vs. motor stage in subject 2). Clearly, if the above assumption is violated, the logic is no longer legitimate. This can be illustrated by comparing subject 1 with subject 3 or 4. The darkened areas represent the prolongations of the processing stages.

ms" delay hits the chain of processing stages *before* response activation has been started up. Obviously, this would favor his/her chances of stopping at this particular delay, complicating the interpretation of the difference in the observed successful inhibition rate (i.e. P(inhibit)).

It should be noted that the above logic only holds in case of a serial and discrete stage structure. In addition, it is assumed that the total difference in mean reaction time between subjects reflects the sum of the prolongations of the processing stages underlying the go task. In the simplified stage models depicted in Fig. 1, this could be recognized in subject 2: the perceptual, central and motor stages are, approximately, slowed down by an equal amount of time.

Thus, a stop task may give preferential treatment to one subject (or subject group) over the other if both subjects (or subject groups) structurally differ in their primary task MRT, even if the inhibition functions are obtained by plotting P(inhibit) as a function of MRT minus delay. In an attempt to overcome this problem, the second purpose of this study is to propose and explore the utility of an alternative method of setting stop signal delay relative to MRT. The method that is suggested tries to account for differences by setting stop signal delays as *proportions* of the subjects' MRT. In practice, this means that, at the start of each block of trials, stop signal delays should be set, for example, at 25%, 50% and 75% of the MRT of the previous block. Whereas the "MRT minus delay" method sets the stop signal delays backward, on the basis of the computed MRT, the present technique includes both the stimulus onset and the expected response, spacing the stop signal delays evenly in between. Hence, this enables the experimenter to present stop signals to subjects who substantially differ in MRT at comparable points along the chain of processing stages. This can be clearly seen in Fig. 1, where setting delays as 25%, 50% and 75% of MRT cause the stop signals – in subjects 1 and 2 – to strike the sequence of stages at corresponding places.

Based on this logic, we hypothesize that the %MRT method, compared to setting stop signal delay as MRT minus delay, is equally capable (at the least) of generating meaningful inhibition functions, capturing the informative part where P(inhibit) slopes between the high and low asymptotes. We additionally hypothesize that, due to the way it corrects for differences in MRT, the %MRT method improves the comparability of inhibition functions from subjects or subject groups that differ in MRT. More specifically, the %MRT method is expected to reduce the between-subject variability around the mean P(inhibit) for each delay, thereby making the mean inhibition function more representative. Clearly, significant differences between inhibition functions will be more likely to occur in this case. To demonstrate this advantage of the %MRT method, we compared – for each stop signal delay – the standard deviation (SD) of the inhibition rate in the %MRT condition with the SD in the MRT – delay condition. It is predicted that the former will be smaller than the latter.

Again, the above line of reasoning is only legitimate if the processing stages that underlie a certain primary task are assumed to be equally prolonged in a slow subject compared to a fast subject (see subject 1 and 2 in Fig. 1). If subjects have, for any reason whatsoever, specific perceptual "deficits" (see subject 3) or motor "deficits" (subject 4), the above argument in favor of setting stop signal delay as %MRT may lose its validity.

It is important to realize that the MRT – delay and %MRT method are procedures that track the subjects' primary task performance block-to-block and set *several* stop signal delays relative to the MRT. Unlike other type tracking methods (for example, trial-to-trial tracking of inhibitory performance – Osman, Kornblum & Meyer, 1986, 1990), the present methods allow for the computation of an inhibition function. Whereas SSRT reflects the *latency* of the internal inhibitory response to a stop signal, inhibition functions, ideally corrected for differences in SSRT, provide us with a measure of the *efficiency* of the executive inhibition process (see Logan, Cowan & Davis, 1984). Therefore, the comparison between the MRT – delay and %MRT method may be of interest especially for researchers who wish to compute inhibition functions in addition to SSRT, or who do not have the opportunity to employ more advanced (dynamic) tracking procedures, for example because their ready-made software package does not allow it.

Method

Subjects. Thirteen students (7 males, 6 females, between 18 and 24 years of age) were paid €7 per hour for participation in the study. All were healthy and had a normal or corrected-to-normal vision.

Apparatus. Stimuli were presented with a 386SX-25 PC, with timing control from a master computer, a 486DX2-66 PC. The master computer recorded the responses. Visual stimuli were presented on a NEC Multisync 5FG monitor (60 Hz refresh rate) positioned at 70 cm from the subject's eyes. Auditory stimuli were administered binaurally through headphones. Subjects were lying on a couch in a dimly illuminated cubicle. A response box was positioned on either side of the couch.

Task and stimuli

(1) *Primary task*. Each trial began with the presentation of a square warning stimulus (1.40 cm × 1.40 cm) illuminated for 500 ms. It was immediately followed by the primary task stimulus, which was displayed for 125 ms. After the imperative signal was extinguished, the screen went blank for a 2375 ms intertrial interval. The stimuli for the primary task were the uppercase letters X and O. Each letter was 1.80 cm wide and 2.90 cm high. Both the warning stimuli and the stimulus letters were presented in black-on-white and in the center of the screen. In the primary choice reaction time task, a capital X required a response with one hand and a capital O required a response with the other. Mapping of letters onto response hands was counterbalanced across subjects.
(2) *Stopping task*. A stop signal was presented on 25% of the trials, occurring equally often at each of 6 stop signal delays, and equally often with an X and an O. The sequence of primary task stimuli,

stop signals, and stop signal delays was pseudo-randomized. In the auditory stop signal-condition, the stop signal was a 1.000-Hz tone, with an intensity of 80 dB(A), 5 ms rise time and 350 ms duration. It was presented binaurally by size-adjustable, padded headphones. In the visual stop signal-condition, the stop signal was a centrally presented red circle with a diameter of 3.60 cm and 350 ms duration. The primary stimulus remained visible inside the red circle when the visual stop signal was presented before the offset of the stimulus letter.

Design and procedure. Three experimental conditions were administered: MRT – delay/auditory stop signal, %MRT/auditory stop signal and MRT – delay/visual stop signal. Each condition consisted of a session of 9 test blocks of 48 trials preceded by a practice block. This means that, for each condition, 9 * (0.25*48)/6 = 18 stop signals were utilized for each stop signal delay. Between sessions, subjects took a short break. The order of sessions was counterbalanced across subjects.

In the MRT – delay condition, the MRT in block n ($n = 1, 2, \dots, 8$) was used to set the stop signal delays in block $n + 1$ equal to MRT – 500, MRT – 400, MRT – 300, MRT – 200, MRT – 100 and MRT – 0 ms. In the %MRT condition, the MRT in block n was used to set the stop signal delays in block $n + 1$ equal to 0.25*MRT, 0.40*MRT, 0.55*MRT, 0.70*MRT, 0.85*MRT and 1.0*MRT. In each session, the stop signal delays in the first test block were set relative to the mean reaction time of the practice block preceding it.

No negative delays were employed. In practice, this meant that the primary stimulus and the stop signal were presented simultaneously in the MRT – 500 condition (in block n) in case the MRT was less than 500 ms (in block $n - 1$).

The standard stop task instruction as prescribed by Logan (1994) was given. This instruction consists of three parts. First, subjects were instructed to be as fast and accurate as possible on the primary go task. Then, they were told to try to withhold the primary response whenever a stop signal occurs. It was explicitly clarified that stop signal delays are varied by the experimenter in such a way that sometimes stop signals will be presented so late that it will be extremely difficult to suppress the primary response. Finally, the subjects were instructed not to delay their responses to the go task in order to improve their odds of stopping.

Data analysis

(1) *Primary task measures*. For each subject and experimental condition, the following primary task measures were derived from the no-stop signal trials: mean reaction time (MRT), standard deviation of MRT (SD), percentage of errors (pressing with the X-hand when O was presented or vice versa) and percentage of omissions (non-responses).

(2) *Inhibition function*. Inhibition functions were generated by computing the proportion of stop signal trials, at each stop signal delay, on which subjects successfully inhibited their primary response (i.e. P(Inhibit)). Effects of sensory modality and tracking method on the probability of inhibition (over all delays) were examined in analyses of variance (ANOVA) with repeated measures across delay. An interaction between delay and experimental factor would then demonstrate differences in the shape of inhibition functions. To look at these differences in shape in a more accurate way, we compared the slopes of regression lines that were fitted to the inhibition functions when they were plotted as a function of the Z Relative Finishing Time (ZRFT) of the stop and go processes (Logan *et al.*, 1984). If inhibition functions are not aligned by setting stop signal delay relative to MRT, differences between experimental conditions may still be an artifact of differences in SSRT and/or of variability in the primary task reaction times. According to the race model, a fast inhibition mechanism wins the race against the go processes more often than a slow one. In general, the faster the SSRT, the higher the inhibition function. With regard to primary task variability, it is predicted that the less variable the distribution, the faster the decrease of the probability of inhibition as a function of suspended stop signal delay, and the steeper the inhibition function. In order to correct for both parameters, the probability of inhibition was also plotted as a function of a Z score that represents the Relative Finishing Time (RFT) of the inhibitory process and primary task process in standard deviation units of the primary task reaction times:

$$ZRFT = \frac{MRT - StopSignalDelay - \overline{SSRT}}{SD_{(MRT)}} \qquad (1)$$

The finish time of the go process is reflected by MRT. The finish time of the stop process can be estimated by adding stop signal delay and mean SSRT (see below for the SSRT estimation procedure). Logically, the relative finishing time is the difference between both estimates, i.e. MRT – (stop signal delay + SSRT), or, formulated differently, MRT – stop signal delay – SSRT.

Since Equation 1 may cause some confusion, it should be emphasized that in the MRT – delay condition "StopSignalDelay" was computed – for each level of stop signal delay – by subtracting 500, 400, 300, 200, 100 and 0 ms from the MRT, respectively, and in the %MRT condition "StopSignalDelay" was computed by multiplying MRT by 0.25, 0.40, 0.55, 0.70, 0.85, and 1.0. The values for "StopSignalDelay" were then used to compute the ZRFTs.

If inhibition functions from different conditions cannot be aligned by plotting them against ZRFT, then it may be concluded that the flatter function represents a "deficiency" in the executive process of inhibition (see Logan *et al.*, 1984).

(3) *SSRT*. To explore more specific deficits in the stopping process, mean SSRTs were estimated for each individual in each experimental condition by means of the following procedure. The point in time at which the stop process finishes was computed from the data by setting it equal to the nth reaction time of the rank ordered go task reaction times, where n is the number of reaction times that make up the distribution multiplied by the observed P(respond) (= 1 – P(Inhibit)). Subtracting stop signal delay from this value yielded the SSRT. It is important to realize that this procedure was carried out for each stop signal delay employed in Experiment 1. The mean SSRT was then obtained by averaging over stop signal delays (see Logan & Cowan, 1984, for an extensive, and more theoretical, discussion on the SSRT estimation procedure).

The effects of stop signal modality (auditory stop signal/MRT – delay vs. visual stop signal/MRT – delay) and tracking method (MRT – delay/auditory stop signal vs. %MRT/auditory stop signal) on the dependent variables were examined by conducting repeated measures analyses of variance (ANOVA) and t-tests.

Results

Mean values and standard deviations for MRT, SD of MRT, percentage of errors, percentage of omissions, inhibition function slope and SSRT are presented for each condition in Table 1.

MRT in the auditory stop signal condition was slower than MRT in the visual stop signal condition, while the results of the analyses on SSRT (see below) showed the reverse pattern (faster SSRT in auditory than in visual stop signal condition). A repeated measures ANOVA performed on the

Table 1. *Performance on the stop signal paradigm as reflected by the means and standard deviations for the dependent measures for each experimental condition*

	Condition					
	MRT – delay (auditory stop signal)		% of MRT (auditory stop signal)		MRT – delay (visual stop signal)	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*
MRT (go task)	560.40	38.78	580.88	52.49	533.48	36.61
SD of MRT	121.27	21.84	113.12	21.15	112.89	22.37
% of errors	1.35	1.19	0.76	0.90	1.16	1.28
% of omissions	1.71	0.37	1.99	0.80	1.83	0.46
Slope (ZRFT)	9.44	6.71	7.39	7.60	5.94	3.07
SSRT	257.35	32.23	246.97	42.40	287.56	41.57

Note: M = mean, SD = standard deviation, MRT = Mean Reaction Time, SSRT = Stop Signal Reaction Time, ZRFT = Z score, Relative Finishing Time. All times are in ms.

Table 2. *Probability of inhibition as a function of stop signal delay and experimental condition*

	Condition		
Stop signal delay (ms)	MRT – delay (auditory stop signal)	% of MRT (auditory stop signal)	MRT – delay (visual stop signal)
MRT – $500_{(25\%*)}$	0.65	0.59*	0.50
MRT – $400_{(40\%*)}$	0.58	0.53*	0.44
MRT – $300_{(55\%*)}$	0.49	0.41*	0.36
MRT – $200_{(70\%*)}$	0.37	0.33*	0.31
MRT – $100_{(85\%*)}$	0.31	0.31*	0.26
MRT – $0_{(100\%*)}$	0.28	0.30*	0.24

reaction times confirmed the interaction between stop signal modality (2 levels: auditory vs. visual) and process (2 levels: go process (MRT) vs. stop process (SSRT)) ($F(1, 12) = 8.42$, $p < 0.05$).

The percentage of both hand errors and omission errors did not exceed 2% in all conditions. Differences in SD of MRT, percentage of errors and percentage of omissions between conditions did not reach significance.

Table 2 presents the mean probability of inhibiting a response to the primary task at each stop signal delay for each condition. Figure 2 displays these probabilities of inhibition as a function of MRT – delay/%MRT and as a function of Z-relative finishing times. Below, we will discuss the experimental manipulations separately, focusing on the inhibition function and SSRT.

Stop signal modality. A two-way analysis of variance (ANOVA) with repeated measures across sensory modality (2 levels: auditory stop signal/MRT – delay and visual stop signal/MRT – delay) and delay (6 levels) was conducted for the probability of inhibition. As predicted by the race model, the probability of inhibition increases significantly as stop signal delay decreases ($F(5, 60) = 15.44$, $p < 0.001$).

Of more importance is the significant main effect obtained for modality ($F(1, 12) = 7.81$, $p < 0.05$). The auditory stop signal condition yielded higher inhibition functions than those observed in the visual stop signal condition. Since the inhibition functions were produced by setting delay relative to mean reaction time (MRT – delay), this effect was not an artifact of the observed difference in response speed to the primary task. Although Fig. 2 suggests that the auditory inhibition function is steeper as well as higher than the visual inhibition function, the interaction between sensory modality and stop signal delay was not significant ($F(5, 60) = 0.70$). To examine the linear component of the interaction more precisely, regression lines were fitted to the inhibition functions plotted against Z-relative finishing time (ZRFT). A t-test revealed that the slope of the regression line in the auditory stop signal condition tended to be steeper than the slope of the regression line in the visual stop signal condition ($t(12) = 1.84$, $p < 0.1$). As the regression lines were fitted to inhibition functions after ZRFT correction, the difference in slope cannot be explained by differences in MRT, SSRT (see below) or primary task variability.

Auditory stop signals speeded the executive process of inhibition if compared to visual stop signals: the estimated

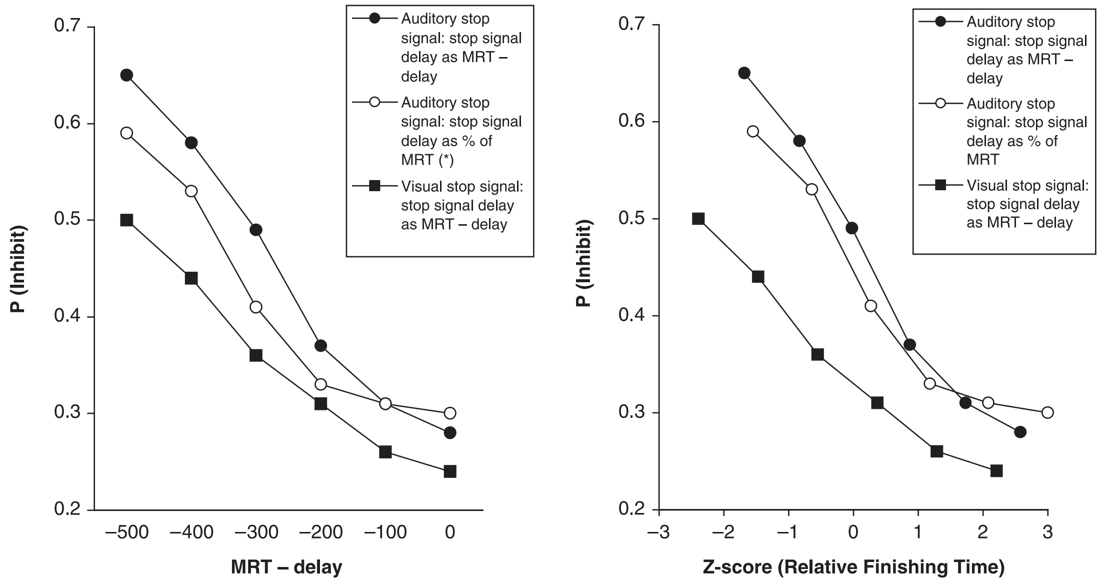

Fig. 2. The probability of inhibition as a function of MRT – delay (left panel) and ZRFT (right panel) for each experimental condition (MRT = Mean Reaction Time, ZRFT = Z score, Relative Finishing Time).
* In the %MRT condition, the MRT in block *n* was used to set the stop signal delays in block *n* + 1 equal to 0.25*MRT, 0.40*MRT, 0.55*MRT, 0.70*MRT, 0.85*MRT and 1.0*MRT.

SSRT to a tone (257 ms) was found to be significantly shorter than the SSRT to a red circle (288 ms; $t(12) = 2.23$, $p < 0.05$).

Tracking method. The mean probability of inhibiting a primary response did not differ between the techniques for setting stop signal delay, as is evident in the absence of a main effect of tracking method in an ANOVA with factors for method (2 levels: MRT – delay/auditory stop signal vs. %MRT/auditory stop signal) and delay (6 levels) ($F(1, 12) = 0.73$). As predicted, the probability of inhibition was strongly affected by stop signal delay ($F(5, 60) = 12.85$, $p < 0.001$). Both methods for setting stop signal delay were affected similarly; that is, the interaction between method and delay was non-significant ($F(5, 60) = 0.29$).

The analyses of the between-subject variability around the mean P(inhibit) showed that the SD was smaller in the %MRT condition compared to the MRT – delay condition at the 55%MRT / MRT – 300 delay (19.7 vs. 22.4), the 70%MRT / MRT – 200 delay (14.5 vs. 21.8) and the 85%MRT / MRT – 100 delay (16.6 vs. 19.6). However, at the 100%MRT / MRT – 0 delay (21.7 vs. 19.6), the 25%MRT / MRT – 500 delay (24.9 vs. 11.7) and the 40%MRT / MRT – 400 (28.8 vs. 23.0) delay, SD was larger in the %MRT condition. The effect of tracking method on SD was marginally significant at the 70%MRT / MRT – 200 delay ($F(12, 12) = 2.26$, $p < 0.1$) and significant at the 25%MRT / MRT – 500 delay ($F(12, 12) = 4.54$, $p < 0.05$).

The tracking methods did not differ in the slope of the inhibition function plotted against ZRFT ($t(12) = 0.74$). As opposed to the auditory and visual inhibition functions described in the previous section, inspection of the inhibition functions generated by the different tracking methods revealed that the ZRFT correction brought them even closer. Tracking method neither had an effect on the speed of stopping (SSRT: ($t(12) = 0.80$) nor on the primary task response speed (MRT: $t(12) = 1.24$).

It should be recognized that the difference in steps between delays in the MRT – delay condition (100 ms) and %MRT condition (87 ms (= 0.15*MRT)) may be somewhat problematic for the graphical representation and statistical analysis of the data. For two reasons, nevertheless, we decided to plot the %MRT inhibition function in the same graph as the MRT – delay inhibition function(s) and conduct the ANOVA as described above. First, plotting P(inhibit) as a function of MRT – delay and %MRT in the same graph is permitted if one considers both as categorical scales ranging from early stop signals (easy to inhibit) to late stop signals (difficult to inhibit). Second, and more importantly, the problem is overcome by plotting P(inhibit) as a function of the Z-scores and performing the analyses on the ZRFT slopes.

Discussion

In the evaluation of the results, the more theoretical issue of setting stop signal delay relative to MRT will be considered first. In particular, the applicability of a technique that sets stop signal delays as proportions of the subjects' MRT will be evaluated. Subsequently, the effects of stop signal modality will be discussed.

Tracking method. The present study intended to explore the practicability (and potential advantages) of an alternative method of setting stop signal delay relative to MRT. It was argued that setting stop signal delay as proportions of the subjects' MRT enables the experimenter to present stop signals to different subjects at comparable points along the sequence of processing stages that underlie the reaction process. The typical MRT – delay tracking method, on the other hand, sets stop signal delays backward from the MRT as a result of which a stop signal at a particular delay might hit different stages (in particular: premotor versus motor) in different subjects.

The proposed %MRT method was hypothesized to yield inhibition functions that are as meaningful as those generated by the MRT – delay method. The analysis of the proportion of stop signal trials, at each stop signal delay, on which the subjects successfully inhibited their primary response indicated that the inhibition functions generated by both tracking methods neither differed in height nor in (ZRFT) slope. Plotting the probability of inhibition as a function of ZRFT brought them into almost perfect alignment. These data strongly support the hypothesis and indicate that setting stop signal delay as %MRT is at least equally capable of yielding a meaningful inhibition function (capturing the informative middle part where the probability of inhibition is between 0.2 and 0.8) as the traditional MRT – delay technique.

In addition, the %MRT method was hypothesized to improve the representativity of an inhibition function by reducing the between-subject variability around the mean P(inhibit) for each delay. The SD analyses showed that the %MRT technique tended to reduce the between-subject variability around the mean P(inhibit) for the intermediate 70%MRT/MRT – 200 delay. For the intermediate 55%MRT /MRT – 300 and 85%MRT/MRT – 100 delays there was a reduction of SD as well, but these effects were not significant.

The finding that the %MRT technique did not positively affect the variability around P(inhibit) at the 25%MRT/ MRT – 500 and 40%MRT/MRT – 400 stop signal delays may be accounted for by assuming that at these early stop signal delays stop signals hit the reaction process at points in time when response activation processes had not been started up yet. As a consequence, the hypothesized advantage of the %MRT technique could not be exploited (although it cannot explain the finding that SD was significantly smaller in the MRT – delay condition than in the %MRT condition at the 25%MRT/MRT – 500 delay). Furthermore, the %MRT method may not have structurally improved the representativity of the inhibition function because we employed a within-subject design, and because the primary task was simple and performed equally fast in the MRT – delay and %MRT condition. Therefore, there may have been less risk that a "MRT – x ms" stop signal (see Fig. 1) systematically hit different stages (in particular: premotor vs. motor) in different subjects.

Since the issue of tracking method may still be of relevance to researchers who intend to design stop task experiments – especially if they plan to work with subjects or subject groups that may differ in MRT – future research should put the alleged positive effect of the %MRT method on the representativity of the inhibition function to the test in a more solid manner. This can be achieved by comparing the MRT – delay and %MRT inhibition function from *different subject groups* who had to perform a primary task with high demands on the processing stages of stimulus identification and response choice. The SD of P(inhibit) should then decide on whether the %MRT inhibition function is more representative than the MRT – delay inhibition function.

Stop signal modality. The sensory modality of a stop signal had an effect on stopping performance in the expected direction: auditory stop signals compared to visual stop signals enhanced both the speed and the efficiency of the inhibition process. The former effect was revealed by differences in the estimated latency of the internal inhibitory response to the stop signal, i.e. SSRT. The latter effect was manifested in the steepness of the inhibition function (marginal effect of sensory modality on ZRFT slope). The modality effect on SSRT can be taken as a function of a transduction delay at the periphery (i.e. chemical photoreception at the retina takes more time than the mechanical reception processes at the ear). In addition, it is a well-established finding that the neural pathway for sound perception is shorter – i.e. has less synaptic transmissions – than the neural pathway for visual perception. Interestingly, the 30-ms difference that was presently observed between visual and auditory SSRT comes close to the classically reported 40-ms difference between simple visual and simple auditory RT (e.g., Elliot, 1968; Goldstone, 1968; Woodworth & Schlosberg, 1954).

The marginal effect of modality on ZRFT slope, on the other hand, is more difficult to interpret and needs some clarification. The tendency for the ZRFT slope to flatten in a visual stop signal condition cannot be explained by differences in MRT, SSRT, and/or differences in primary task variability since regression lines were fitted to the inhibition functions after ZRFT correction. Clearly, a correction for SSRT was necessary since SSRT in the auditory stop signal condition was faster than SSRT in the visual stop signal condition, and a correction for MRT was necessary since the MRT in the visual stop signal condition was faster than the MRT in the auditory stop signal condition (see below for a possible explanation for this intriguing effect). Therefore, we are left with the following questions: what factors brought about the residual differences in inhibition functions after ZRFT correction, and how should they be interpreted? Logan and Cowan (1984) hypothesized that – in addition to a deficiency in triggering the inhibition process – the slope of an inhibition function will flatten due to greater variability in the stop process. Since an increase in latency is typically associated with an increase in variability, the trend for the ZRFT slope to flatten in the visual stop signal condition as compared to the auditory stop signal condition may therefore be explained (at least in part) by the same basic perceptual differences between the modalities as indicated above.

However, this does not explain the finding that in the auditory stop signal condition, the better stopping performance (short SSRT) was associated with a low performance on the primary task (long MRT), and that in the visual stop signal condition, the worse stopping performance (long SSRT) was associated with a high performance on the primary task (short MRT). In fact, this finding led us to suspect that a mere perceptual account of the modality effect on motor stopping disregards an alternative explanation that may be compatible with the results as well. As we will argue below, a difference in their arousing qualities may have contributed not only to the finding that auditory stop signals resulted in a better stopping performance than visual stop signals but also to the finding that subjects slowed down their primary response speed especially when an auditory stop signal were presented.

Evidence that auditory and visual stimuli differ in their arousing qualities stems from reaction time experiments employing the additive factors method (Sternberg, 1969). It has been found that tones *that are sufficiently loud* reduce the effect of foreperiod duration by shortening RT especially at long foreperiods (Keuss & Van der Molen, 1982; Sanders, 1975; Van der Molen & Keuss, 1979, 1981). The interaction between signal intensity and foreperiod duration was not found with visual signals (Sanders, 1975, 1977) or only at really high intensities (Niemi & Näätänen, 1981). Based on the assumption that foreperiod duration affects motor processes, the interaction between signal intensity and foreperiod duration has been described as an effect of "immediate arousal" (Sanders, 1975, 1977, 1980). In short, immediate arousal is believed to cause a direct activation of motor channels (see Sanders, 1998, for an overview). However, a signal can only evoke an effect of immediate arousal if time uncertainty is high. Only then, preparation for a response is low and preparatory state may leave room for immediate arousal to facilitate motor processes. Another requirement for immediate arousal to manifest itself is that demands on response selection must be minimal. Since all computational processing stages are bypassed, only simple tasks can benefit from the direct activation of motor channels.

If the above logic is generalized to the stop task, the conditions for immediate arousal to take action should be considered favorable. For two reasons, we argue that in Experiment 1 the auditory stop signals may have elicited effects of immediate arousal. First, time uncertainty was high since the stop signal was only presented occasionally and with a variable delay. Second, response selection demands were low: the stop signal only required the complete cancellation of the initiated response activation processes. Since immediate arousal could facilitate the direct activation of motor processes, – in this case: processes engaged in the inhibition of a response – subjects may have profited from the arousing properties of auditory stop signals (but not visual stop signals) throughout the stop task.

The suggestion that auditory and visual signals differ in their arousing qualities is in line with Sanders' (1977) conclusion that "man has an internal arousal dimension, sensitive to signal intensity, but having different values for different sensory modalities" (more sensitive to auditory than to visual intensity; see also Posner, Nissen & Klein, 1976). In other words, stop tones are more likely to elicit effects of immediate arousal because they are perceived as being more intense than visual stop signs. Possibly, this may explain the finding that mean RT on go trials was slower in an auditory stop signal condition than in a visual stop signal condition. Under the assumption that auditory stop signals are psychophysically stronger than visual stop signals, we may have produced a stronger tendency to expect a stop signal when these are presented in the auditory modality. It is a well-known phenomenon that subjects performing a stop task sometimes deliberately hold back their response to the primary task in order to enhance their probability of successful inhibition. The present study suggests, however, that subjects may engage in this undesirable "fail-safe" strategy especially in an auditory stop signal condition.

EXPERIMENT 2

To further investigate the arousing properties of auditory stop signals, we decided to conduct an experiment in which their intensity was varied. Specifically, we administered stop tones with an intensity of 60 dB(A) and 80 dB(A). Previous research has shown that an auditory signal is capable of evoking an effect of immediate arousal only if its intensity exceeds a threshold around 70 dB(A) (e.g., Sanders, 1975, 1977). In view of the direct mobilization of motor channels, we therefore expect immediate arousal to facilitate stopping performance (i.e. speed up SSRT) especially in the 80 dB(A) condition.

To test the hypothesis that subjects engage in a strategy of holding back primary response speed more in an auditory stop signal condition than in a visual stop signal condition, we also administered a block of trials in which no stop signals were presented so as to establish the "baseline" primary response speed. Prolongation of mean RT was then determined in the visual stop signal condition, the 60 dB(A) auditory stop signal condition and the 80 dB(A) auditory stop signal condition. Assuming that loud tones cause more physiological arousal than weak tones, we hypothesize that subjects delay their primary responses, and await the possible appearance of a stop signal, especially in the 80 dB(A) auditory stop signal condition.

Method

Seventeen subjects (9 men and 8 women, between 22 and 35 of age) participated in Experiment 2, which was controlled by a Pentium 4 2.8 GHz computer running E-prime software.

Four experimental conditions were administered: (1) a no stop signal condition, (2) a visual stop signal condition, (3) a 60 dB(A) auditory stop signal condition and (4) a 80 dB(A) auditory stop signal condition. Apart from the intensity manipulation, the same stimuli and the same (primary and stopping) task were used as in Experiment 1.

Each condition consisted of one block of 120 trials, the order of which was counterbalanced across subjects. A stop signal was presented on 25% of the trials. However, in comparison with Experiment 1, yet another tracking procedure was employed. Simulation studies have shown that tracking the subjects' stopping ability may be a better way to estimate inhibition efficiency than solely tracking their primary task performance (e.g., Band, 1997; Band, Van der Molen & Logan, 2003). Band *et al.* found the estimation of SSRT to be most reliable around the central delay, where subjects have a 50% chance of successful inhibition. One way to set the inhibition rate at 50% throughout a stop task is to use the staircase tracking algorithm developed by Osman, Kornblum and Meyer (1986, 1990). This algorithm tracks the inhibition rate trial-to-trial by adjusting the stop signal delays according to a rule based on whether a subject had responded or inhibited on previous stop signal trials. In Experiment 2, stop signal delay was increased by 50 ms every time the subject inhibited, and decreased by 50 ms every time the subject responded. It is established that, when delays are set by this rule, subjects respond on half of the stop signal trials and inhibit on half of the stop signal trials. This means that on average, the go and the stop process finish at the same time. Accordingly, the finish time of the go process becomes an estimate of the finish time of the stop process (i.e. SSRT). SSRT can be calculated by subtracting the mean stop signal delay from the mean primary task reaction time.

Experiment 2 enabled us to compare SSRT obtained with a stop task in which stop signal delays are set trial-to-trial according to the subject's inhibitory performance to SSRT obtained with a stop task in which stop signal delays are set block-to-block according to the subject's primary task performance (as we did in Experiment 1).

Results

We predicted subjects to inhibit on about half of the stop signal trials. This assumption proved to be warranted since the overall ratio was 51.5% inhibition / 48.5% response.

A repeated measures ANOVA performed on the reaction times corroborated the interaction between stop signal modality (visual stop signal vs. 80 dB(A) auditory stop signal) and process (go process (MRT) vs. stop process (SSRT)) that was found in Experiment 1 ($F(1, 16) = 13.76$, $p < 0.005$). The interaction was also significant when the 60 dB(A) instead of the 80 dB(A) auditory stop signal reaction times were entered into the ANOVA ($F(1, 16) = 5.87$, $p < 0.05$). In addition, there was a significant interaction between intensity (80 dB(A) auditory stop signal vs. 60 dB(A) auditory stop signal) and process (MRT vs. SSRT) ($F(1, 16) = 16.09$, $p < 0.001$).

Figure 3 presents the *increase* in mean primary task reaction time (MRT) in the stop signal conditions compared to the MRT in the baseline no stop signal condition (= 360.2 ms) (left panel) as well as the SSRT in the stop signal conditions (right panel).

As predicted, the increase in MRT was larger in the 80 dB(A) auditory stop signal condition (+113.1 ms) than in the visual stop signal condition (+39.8 ms: $t(16) = 2.6$, $p < 0.05$) and 60 dB(A) auditory stop signal condition (+59.9 ms: $t(16) = 2.8$, $p < 0.05$). The prolongation of MRT in the 60 dB(A) auditory stop signal condition did not significantly differ from the prolongation of MRT in the visual stop signal condition ($t(16) = 1.5$).

The SSRTs showed the reverse pattern. The stopping process was significantly faster in the 80 dB(A) auditory stop signal condition (187.0 ms) than in the visual stop signal condition (241.0 ms: $t(16) = 3.4$, $p < 0.005$) and 60 dB(A) auditory stop signal condition (211.0 ms: $t(16) = 2.5$, $p < 0.05$). The difference between SSRT to the 60 dB(A) tones and visual signals was also significant ($t(16) = 2.4$, $p < 0.05$).

GENERAL DISCUSSION

Experiment 2 yielded faster SSRTs than Experiment 1 (respectively, 241.0 ms and 287.6 ms in the visual stop signal condition, and 187.0 and 257.4 in the 80 dB(A) stop signal

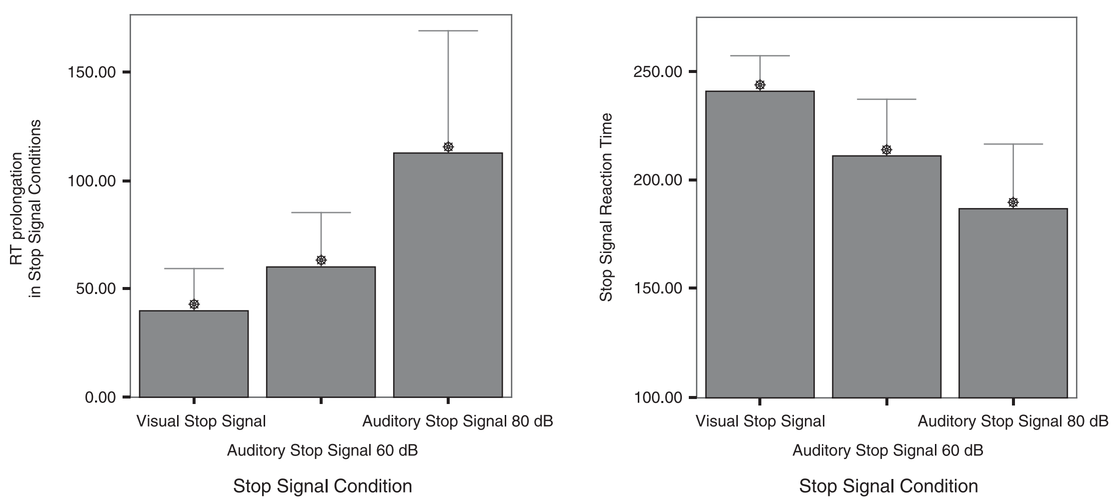

Fig. 3. The *prolongation* of mean primary task reaction time (MRT) (+SE) in the stop signal conditions compared to the MRT in the baseline no stop signal condition (= 360.2 ms) (left panel), and SSRT (+SE) in the stop signal conditions (right panel).

condition). This effect may be accounted for by differences in the characteristics of the two tasks. In Experiment 1, stop signal delays in each *block* were set relative to the mean *reaction time* of the preceding block (either MRT – delay or %MRT). In Experiment 2, stop signal delays were set in each *trial* according to a rule based on whether a subject had *responded or inhibited* on the preceding trial. The advantage of the tracking procedure used in Experiment 2 is that SSRT can be estimated around a central delay where the inhibition rate is 50%, and that it corrects for the tendency to wait for the stop signal within rather than between blocks of trials. However, how these differences in tracking procedure affect performance is not clear. Interestingly, Kooijmans, Scheres and Oosterlaan (2000) found a similar difference between SSRT obtained with a stop task with fixed intervals and SSRT obtained with a stop task with the staircase tracking algorithm. We agree with their conclusion that "future research will be needed to address the issue of possible differences between the two methods of assessing inhibitory control" (p. 182).

Experiment 2 confirmed the finding of Experiment 1 that auditory SSRT was faster than visual SSRT, but it showed that the modality effect was larger for 80 dB(A) auditory stop signals (54 ms decrease) than 60 dB(A) auditory stop signals (24 ms decrease). Whereas the 60 dB(A) auditory stop signal – visual stop signal difference and at least part of the 80 dB(A) auditory stop signal – visual stop signal difference in SSRT can be explained by the previously described perceptual differences between the modalities, the 80 dB(A) auditory stop signal – 60 dB(A) auditory stop signal difference in SSRT can certainly not. The effect of auditory stop signal intensity supports the hypothesis that loud tones are more capable of evoking effects of immediate arousal than weak tones, and that subjects can profit from this in a stop experiment. Immediate arousal is believed to cause a direct activation of motor processes and helps to explain the well-established finding that subjects show shorter reaction times in response to louder tones than to weak tones (e.g., Jaskowski, Rybarczyk & Jaroszyk, 1994). The results of Experiment 2 suggest that this logic does not only apply to responses to an auditory *go* signal but also to responses to an auditory *stop* signal.[1]

Subjects performing a stop task almost inevitably feel inclined to delay their response to the primary task in order to enhance their probability of successful inhibition. This may explain why a simple X–O choice reaction time task yields mean RTs of 580 ms (Experiment 1, this study) or even 660 ms (Schachar & Logan, 1990) when it is used for a stop task. The MRT results from Experiment 2 showed that subjects adopt such a "fail-safe" strategy more in an auditory stop signal condition than in a visual stop signal condition but only when the intensity of the auditory stop signals exceeds a particular threshold (supposedly around 70 dB(A)). Presumably, stop tones that are sufficiently loud cause a physiological arousal which induce subjects to increase their tendency to delay their responses to the primary task. It should be realized that subjects who intentionally persist in carrying out this strategy may even endanger the validity of the stop task. As soon as these subjects realize that the stop signal delay has been prolonged once again they simply slow down their primary reaction speed accordingly. After all, their only intention is to keep up with their "stopping record". Obviously, a stop task loses its validity if a subject just plays along with the experimenter, slackening primary response speed step by step.

NOTE

[1] Possibly, the SSRT data may also be accounted for, at least in part, by the selective operation of the orientation reaction (OR), an arousal concept closely related to immediate arousal. The OR is elicited by novel and intense stimuli. Like immediate arousal, it is involuntary and brief in duration. Whereas the effect of immediate arousal is mainly described in terms of presetting motor adjustment, the OR is believed to result in a complete cancellation of all ongoing behaviors (Lynn, 1966; Sokolov, 1963). Noteworthy, non-selectively interrupting all ongoing actions is exactly what a stop signal calls for. As stronger stimuli evoke stronger reactions (Lynn, 1966) and subjects are sensitive to signal intensity especially in the auditory modality (Posner *et al.*, 1976; Sanders, 1977), auditory stop signals are more likely to have elicited ORs than visual stop signals.

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